AN EXTENDING FITTS' LAW FOR HUMAN UPPER LIMB PERFORMANCE EVALUATION

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Abstract- **Human motor behavior is complex and is challenging to understand. Fitts' Law presented a relationship between speed, accuracy, amplitude of movement and target size in upper extremity tasks. In this paper, Fitts' Law was extended from one-dimensional motion to two-dimensional motion in the polar coordinate system for the human upper limb performance. Based on this, a set of indices were proposed. The index of difficulty and the index of performance were introduced as the general indices for the quality measure of plane pointing movement, which is a basic functional action of upper-limb in human daily life. Five healthy subjects were asked to perform six pointing tasks with different indices of difficulty. All movements were recorded using a Vicon motion analysis system. The movement quality was evaluated using these evaluation indices.**

Keywords **- Synergy, pointing movement, upper limb, motion pattern, motion quality**

I. INTRODUCTION

Human motion quality measure is of great significance in biomedical engineering such as the movement disorder and pathology diagnoses and rehabilitation evaluation. For this reason, a large number of motion quality metrics have been developed [1]. However, these quality measures are mostly dependent on the clinicians' experience (e.g., subjective estimates by skilled human raters) about the movement being investigated.

Early in 1954, Fitts introduced [2] a mathematical relationship between speed, accuracy, amplitude of movement, and target size for upper extremity tasks. This relationship, known as Fitts' Law derived using basic information theory constructs of Shannon, provides a basis for objectively measuring neuromuscular performance capacities in one-dimensional translational motion. The index of difficulty, I_d, and index of performance, I_p, are defined as:

$$I_d = -\log_2(W/2A); \qquad (1)$$

$$I_p = -\frac{1}{t_m}\log_2(W/2A) \qquad (2)$$

where A is the movement amplitude, W is the target width, t_m is the target-to-target movement time.

In 1995, Kondraske developed [3] Fitts' Law to measure the performance of one-dimensional angular motion that is a common case in any task involving one or more jointed body segments.

The index of difficulty and index of performance are defined as:

$$I_d{}^{\theta} = -\log_2(\theta_W/2\theta_A); \quad (3)$$

$$I_p{}^{\theta} = -\frac{1}{t_m}\log_2(\theta_W/2\theta_A) \qquad (4)$$

where θ_A is the movement amplitude of angular motion, θ_W is the target width, and t_m is the target-to-target movement time.

However, the movement of the whole upper limb can not be studied as one-dimensional motion. In this paper, the Fitt's Law was extended to plane motion in a polar coordinate system. It is established on the hypothesis that the two freedoms have no cross-talk on the neuromuscular performance capacity.

Due to the variability and complexity of the tasks, the nature of free arm movements is completely different from being restricted, repeatable or cyclic as compared to gait. In contrast to gait for the lower limb, there are no standard activities for the arm. But if arm motion analyses are routinely used for diagnosis or rehabilitation, a set of discriminating (i.e. normal versus pathological) tasks or a set of desired functional tasks could be established. Activities of daily living (ADL) have been studied in order to establish the requirements for orthoses or prostheses and to provide input to biomechanical models [4].

Among the activities of daily living, reaching has the highest priority [5]. The pointing movement was analysed in this study. To the specific movement, the index of difficulty and index of performance have been defined in detail together with a set of other evaluation indices.

II. METHODOLOGY

Fig.1 shows the pointing movement of upper-limb in a sagittal plane. The parameters are defined as follows, P_s the position of shoulder center, P_{ini} the initial position of arm tip, P_{ter} the terminal position of arm tip, θ_i the initial position angle, θ_t the terminal position angle, l_i the horizontal distance between P_s and P_{ini}, h_i the level difference between P_s and P_{ini}, l_t the horizontal distance between P_s and P_{ter}, and h_t the level difference between P_s and P_{ter}. Because of the anatomical differences among subjects, it is necessary to normalize the pointing movement task in the experimental investigation. The two pointing movement tasks will be considered as identical on the following conditions, 1) two pointing movement task have the same θ_i, θ_t, and $(l_t - l_i)/l_0$ or $(h_t - h_i)/l_0$, where l_0 is the length of the arm, 2) the joints of upper-limb (shoulder, elbow and wrist) are at their neutral positions as the movement starts and ends, and 3) The target is in front of the start position, and during the task performance, the arm tip are kept forward with no yaw to the right or left. Five subjects involving in the investigation were young and healthy male. The average age,

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Abstract

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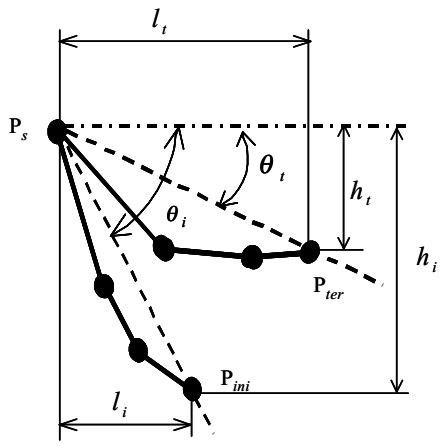

Fig. 1. The initial and terminal positions of pointing movement of upper limb in a sagittal plane

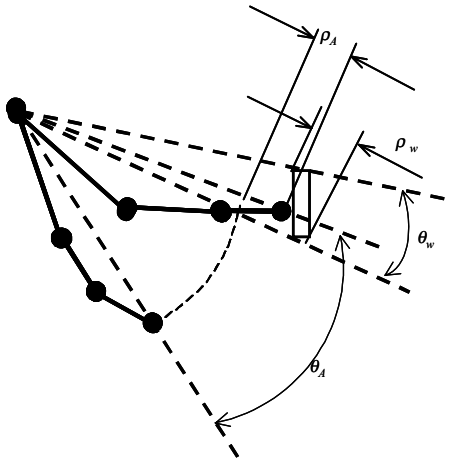

Fig. 2. Movement amplitudes and target parameters in a polar coordinate system

stature and body mass were 28±2 year, 1.74±0.04 m and 62±5 kg. Each was asked to perform 6 pointing movement tasks with different indices of difficulty. Three tasks had the same h_i and h_t, but different in horizontal distance, and the other three had the same l_i and l_t but different in level. The geometrical parameters are listed in Tables 1 and 2.

To distinguish the movements in same pattern but in different grades, and also to evaluate the movement performance, a set of quantitative indices were defined based on Fitts' Law.

Assuming that the two freedoms have no cross-talk on the neuromuscular performance capacity, Fitts' Law can be extended to two-dimensional motion. In a polar coordinate system the index of difficulty and index of performance are defined as:

$$I_d{}^{\rho} = -\log_2(\rho_W / 2\rho_A); \qquad (5)$$

$$I_p{}^{\rho} = -\frac{1}{t_m}\log_2(\rho_W / 2\rho_A) \qquad (6)$$

TABLE 1
The parameters of three pointing movement tasks of upper-limb (different degrees in horizontal distance)

Task	θ_i (°)	θ_t (°)	$(l_t - l_i)/ l_0$
Long distance	50	17	0.33
Normal distance	50	21	0.30
Short distance	50	27	0.27

TABLE 2
The parameters of three pointing movement tasks of upper-limb
(different degrees in vertical level)

Task	θ_i (°)	θ_t (°)	$(h_t - h_i)/ h_0$
High level	50	5	0.59
Normal level	50	18	0.30
Low level	50	27	0.27

$$I_d{}^{\theta} = -\log_2(\theta_W / 2\theta_A); \qquad (7)$$

$$I_p{}^{\theta} = -\frac{1}{t_m}\log_2(\theta_W / 2\theta_A) \qquad (8)$$

where $I_d{}^{\rho}$ and $I_d{}^{\theta}$ denote the task difficulty, $I_p{}^{\rho}$ and $I_p{}^{\theta}$ denote the neuromuscular channel capacity associated with index finger, ρ_A and θ_A are the motion amplitude, ρ_W and θ_W are the target width (see Fig. 2), t_m is the target-to-target movement time.

In the present study, the movement tasks had same target, so the index of difficulty and index of performance can be simplified as:

$$I_d{}^{\rho} = -\log_2(1/2\rho_A); \qquad (9)$$

$$I_p{}^{\rho} = -\frac{1}{t_m}\log_2(1/2\rho_A); \qquad (10)$$

$$I_d{}^{\theta} = -\log_2(1/2\theta_A); \qquad (11)$$

$$I_p{}^{\theta} = -\frac{1}{t_m}\log_2(1/2\theta_A) \qquad (12)$$

The velocity index ($\bar{v}$) is defined as the average speed throughout a task. The acceleration time constant is defined as

$$\tau_A = V_A / A_M , \qquad (13)$$

where V_A is the velocity at maximal acceleration and A_M is the actual maximal acceleration. This index represent the time interval during which the upper-limb accelerates from muscle moment (M) is from zero to its peak value M [6]. The time index, T, is the time spent on the task, in this paper, $T = t_m$.

The Power index is defined as the total energy (E_T) consumed in the whole movement [7]. The Smoothness index, $\bar{S}$, is the average instantaneous smoothness index, S, throughout a task. The instantaneous smoothness is defined as:

$$S = \frac{1\times 10^{8}}{|J_X|\cdot|J_Y|\cdot|J_Z|} \qquad (14)$$

where J_X , J_Y , J_Z are the differential of acceleration in *X-, Y-, Z*-axis direction respectively.

The velocity, power and smoothness indices are very gross estimates of a movement. On some occasions, more statistics parameters of variables describing the movement are required. As a supplement, the following parameters will be used as accessory indices :

The covariance of speed $C_v = Cov(V)$;
The maximal instantaneous speed $M_v = Max(V)$;
The maximal instantaneous kinetic energy,
$M_{ip} = Max(K_E)$; (K_E is the instantaneous kinetic energy)
The covariance of smoothness,
$C_s = Cov(S)$;
The maximal instantaneous smoothness,
$M_s = Max(S)$.

III. Results

Tables 3 and 4 show one typical corresponding indices of different tasks performed by the same subject.

It can be seen in Table 3 that as the task becomes easier, the I_d^{ρ} and I_d^{θ} decrease with the I_p^{ρ} and I_p^{θ} increase. But in Table 4 which shows the indices of tasks different in vertical distance, the I_p^{ρ} and I_p^{θ} of moderate is the best. This is because there is an " appropriate " distance between the subject and target, subject felt little comfortable if it is too high or too low, and the quality of task performance become worse accordingly.

The results show that the indices of movement performance quality presented in this paper, especially the general motion quality metrics for 2-D planar motion in a polar coordinate system provid a set of objective and quantitative human motion evaluation indices which may have a great potential applications to biomedical engineering.

IV. Discussion

The results of the experiments show that the different tasks have the topological invariance in trajectories. The invariance can be more clearly found in the normalized data of the arm tip, shown in Fig.3, the planar trajectories of arm tip from different tasks performed by the same subject. The trajectories after normalization are similar, and the different tasks can be seen as the same movement pattern. Based on this, the indices have been used to evaluate the quality of the movements in same movement pattern but in different degrees.

Flash observed [8] the roughly straight trajectories with single-peaked and bell-shaped speed profiles when the hand moved between pairs of targets in the horizontal plane. The trajectories obtained in this study are not simple straight lines, but an arc at the end. It is also observed that the trajectory alters when the start position changed. Although the trajectories are all smooth and straight in most part, the difference can be obviously found at the start and the end parts, which can be expressed using the value of indices. This indicates that the movement performance of upper-limb is determined by not

TABLE 3
The indices of different tasks performed by the same subject
(different degrees in horizontal distance)

Motions	I_d^{ρ}	I_p^{ρ}	I_d^{θ}	I_p^{θ}	τ_A (s)	T (s)	$\bar{v}$ (mm.s^{-1})	C_v (mm^2.s^{-2})
Long distance	8.9321	8.1821	6.0444	5.5367	0.2292	1.0917	483.1098	166430
Normal distance	8.5926	8.5216	5.9069	5.8583	0.2171	1.0083	467.7477	165290
Short distance	8.0753	8.7300	5.5236	5.9715	0.2894	0.9250	471.3628	109320

Motions	M_v (mm.s^{-1})	$\bar{S}$ (s^9.mm^{-3})	C_s (s^{18}.mm^{-6})	M_s (s^9.mm^{-3})	E_T (N.m)	M_{ip} (N.m)
Long distance	1410	25.5924	88.5621	34.8620	25.905	0.99399
Normal distance	1357.3	47.7170	63.8193	76.4332	22.962	0.92109
Short distance	1122.1	35.1571	19.9921	50.3752	18.178	0.62954

TABLE 4
The indices of different tasks performed by the same subject
(different degrees in vertical level)

Motions	I_d^{ρ}	I_p^{ρ}	I_d^{θ}	I_p^{θ}	τ_A (s)	T (s)	$\bar{v}$ (mm.s^{-1})	C_v (mm^2.s^{-2})
High level	9.4731	7.0607	6.4919	4.8386	0.2152	1.3417	460.5404	204570
Normal level	8.6087	7.8859	6.0000	5.4960	0.1223	1.0917	442.1837	150330
Low level	8.4108	7.3732	5.5236	4.8380	0.3390	1.1417	507.7467	257090

Motions	M_v (mm.s^{-1})	$\bar{S}$ (s^9.mm^{-3})	C_s (s^{18}.mm^{-6})	M_s (s^9.mm^{-3})	E_T (N.m)	M_{ip} (N.m)
High level	1475.8	17.9178	97.5111	50.3870	33.231	1.0890
Normal level	1396.8	4.6324	77.3236	31.4061	22.405	0.97547
Low level	2787.0	2.1095	24.4016	8.6632	41.063	3.8837

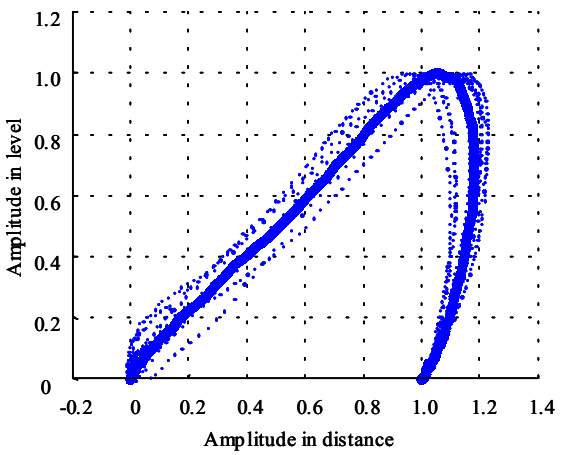

Fig. 3. The normalized arm tip trace in sagittal plane. Dot lines are the traces of one subject in different movements with different index of difficulty .

only the movement pattern but also the start and the end positions. Another possible factor affecting the performance is the body posture. The performance is also influenced by the states of the subjects. It is found that the indices of performance and smoothness drop when subjects had repeated the same tasks for many times, possibly due to the tiredness.

It should be mentioned that motion quality reflects many different aspects. It is almost impossible to entirely describe the quality of a movement in one or several indices. For studies in the human movement synergy, the index of performance, the smoothness index and the power consumption index should be analyzed first.

The indices of motion quality as part of the standard indices for a certain movement pattern can be used in biomechanical modeling, orthoses design and control. The indices are different between the normal and abnormal subjects when they performance the same movement task. There are differences between well and unwell conditions for the same subject. They can be used to evaluate the rehabilitation treatment and process.

V. Conclusion

Fitts' law is extended from one-dimensional motion to two-dimensional motion in the polar coordinate system. A set of indices are presented to evaluate the human movement performance, which are meaningful in biomedical engineering.

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